Terahertz Radiometer Design for Traceable Noise-Temperature Measurements

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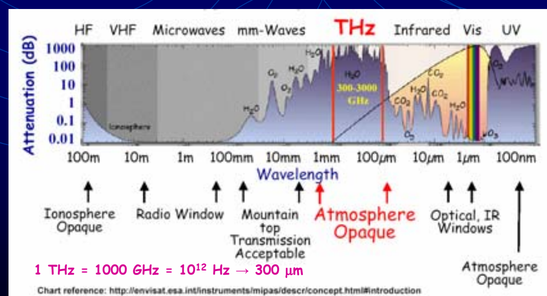
Outline

- Motivation
- Terahertz radiometer design
- HEB mixer technology
- MMIC low–noise amplifier
- Blackbody materials for terahertz frequencies
- Cryogenic setup
- Summary

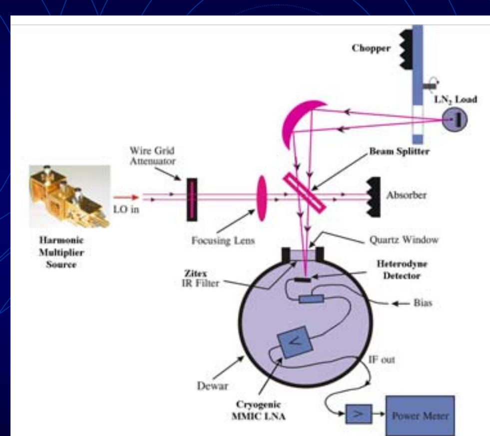
Motivation

- Terahertz imaging and spectroscopy has great potential for both healthcare & homeland security applications.
- However, development of terahertz heterodyne detection systems is impeded by the inability to characterize noise properties (& therefore the sensitivity) of such systems.
- Need noise-measurement ability to characterize the basic performance of any system that detects or processes weak terahertz signals.
- There is also a need for standard methods for characterizing basic individual components, such as quasi-optical adapters or windows.
- We're designing and building a system for traceable noise-temperature measurements at terahertz frequencies.



Terahertz Radiometer for Traceable Noise-Temperature Measurements

- Front-end heterodyne detector integrated with MMIC LNA on same mixer block.
- Quasi-optical configuration.
- Block mounted in 4-7 K ambient temperature using mechanical cryocooler system for (relatively) quick access.
- LO is a commercial harmonic multiplier source capable of hundreds of μW.
- Both the LO and the incident terahertz signals are combined using thin mylar beam splitter.

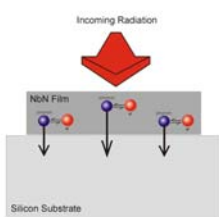


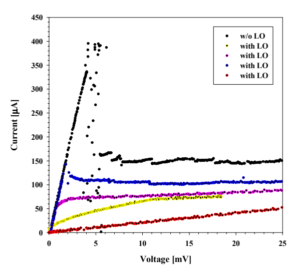
Terahertz Local Oscillator (LO) Technologies

- Far Infrared (FIR) Lasers
  - Pros: high power, stable, many lines.
  - Cons: expensive, not tunable, size.
- Harmonic multipliers
  - Pros: stable, highly tunable, size.
  - Cons: low power, expensive, does not work at the higher terahertz range.
- Quantum Cascade lasers (QCL)
  - Pros: potentially high power, somewhat tunable, size.
  - Cons: not available, temperature stability, does not work at the lower terahertz range.
- Free electron lasers (FEL)
  - Pros: potentially high power, tunable, simplicity.
  - Cons: not available, size, x-ray emission.

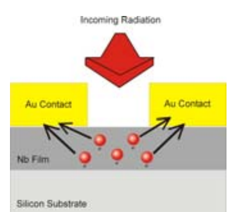
What is a Hot Electron Bolometric (HEB) mixer?

PHEB:





DHEB:



- HEBs are made of superconductors.
- Two types of HEBs:
  - Phonon–Cooled (PHEB), NbN
  - Diffusion-Cooled (DHEB), Nb
- Device volume as small as 2 µm by 0.5 µm by 3.5 nm (PHEB), and 0.1 µm by 0.08 µm by 10 nm (DHEB).

PHEB:

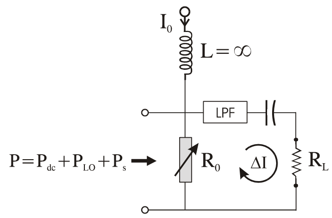
$$c_e(\theta)\,v\frac{\partial\theta}{\partial t} = -K_1(\theta;T_p) + VI + \alpha_p\left[\sqrt{P_s}\exp(j\omega_s t) + \sqrt{P_{LO}}\exp(j\omega_{LO} t)\right]^2$$

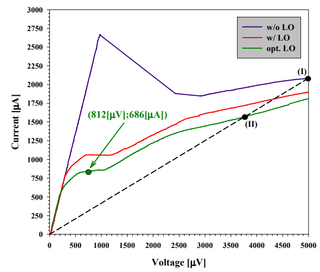
$$c_p(T_p)\,v\frac{\partial T_p}{\partial t} = -K_2(T_p;T_0) + K_1(\theta;T_p)$$

$$K_1 = v\frac{c_e(\theta - T_p)}{\tau_{e-p}}$$

$$K_2 = v\frac{c_p(T_p - T_0)}{\tau_{es}}$$

Modeling of PHEB





$$L_c = \frac{1}{2(C_0 I_0)^2} \frac{(R_L + R_0)^2}{R_L P_{LO} \alpha_P^2} \left(1 - C_0 I_0^2 \frac{R_L - R_0}{R_L + R_0}\right)^2 \left(1 + (\omega_{IF} \tau_m)^2\right)$$

power heating coefficient: $C_0 = \frac{dR}{dP} = \frac{1}{I_0^2} \frac{\frac{\Delta V}{\Delta I}\frac{I_0}{V_0} - 1}{\frac{\Delta V}{\Delta I}\frac{I_0}{V_0} + 1} = \frac{R_0}{P_{dc}} \frac{\left(\frac{dV}{dI}\right)_{dc} - R_0}{\left(\frac{dV}{dI}\right)_{dc} + R_0}$

$$\Rightarrow \quad G = 2\left(C_0 I_{00}^2\right)^2 \left(\frac{I_0^2}{I_{00}^2}\right)\left(1 - \frac{I_0^2}{I_{00}^2}\right) \frac{R_L}{R_0} \frac{1}{\left(\frac{R_L}{R_0} + 1\right)^2} \frac{1}{\left[1 - C_0 I_{00}^2 \frac{I_0^2}{I_{00}^2} \frac{\frac{R_L}{R_0} - 1}{\frac{R_L}{R_0} + 1}\right]^2}$$

- Gain bandwidth determined by the thermal time constant τ, $\tau = \tau_{p-e} + \tau_{esc}$ $\Rightarrow$ $B_G = \frac{1}{2\pi\tau}$
- Noise bandwidth is about 2 times the gain bandwidth (8-10 GHz).

HEB Noise Mechanism

$$F = \frac{S_i / N_i}{S_o / N_o} \qquad F = \frac{(P_n)_{out}}{G k_B T B} \qquad T_e = (F - 1) T_0$$

$$T_{e_{cas}} = T_{e1} + \frac{T_{e2}}{G_1} + \cdots + \frac{T_{en}}{G_1 G_2 \cdots G_{n-1}}$$

$$F_{cas} = F_1 + \frac{F_2 - 1}{G_1} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}}$$

$$P^{Planck} = k_B T B \left(\frac{\frac{hf}{k_B T}}{\exp^{\frac{hf}{k_B T}} - 1}\right)$$

$$P_1 = G k_B T_1 B + G k_B T_e B$$
$$P_2 = G k_B T_2 B + G k_B T_e B$$

$$Y = \frac{P_2}{P_1} = \frac{T_2 + T_e}{T_1 + T_e}$$

$$T_e = \frac{T_1 - Y T_2}{Y - 1}$$

$$T_{TF} = \frac{\langle P_n \rangle}{k_B} = \frac{\frac{4\theta^2 \tau_\theta}{C_e v}\left(\frac{\partial R}{\partial \theta}\right)^2 I_0^2 R_L}{\left(\frac{R_0 + R_L}{1 - C_0 I_0^2}\right)^2 \left(1 + C_0 I_0^2 \frac{R_0 - R_L}{R_0 + R_L}\right)^2}$$

$$T_J = \frac{\langle P_n \rangle}{k_B} = \frac{4\theta R_0 R_L}{\left(\frac{R_0 + R_L}{1 - C_0 I_0^2}\right)^2 \left(1 + C_0 I_0^2 \frac{R_0 - R_L}{R_0 + R_L}\right)^2}$$

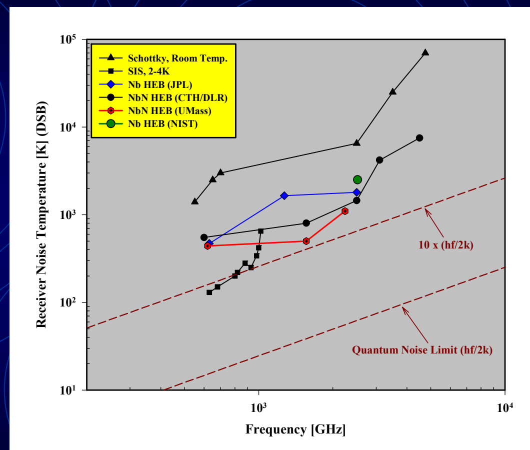
$$T_{out} = T_{TF} + T_J$$

$$\Downarrow$$

$$T_{R,DSB} = \frac{L_C}{2}\left(T_{out} + T_{IF}\right)$$

Receiver Noise Temperatures at Terahertz Frequencies

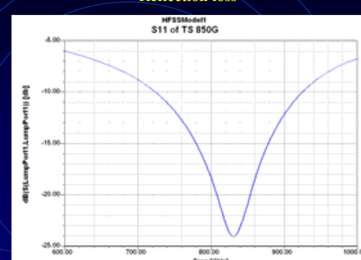
- NbN PHEBs have demonstrated $T_{R,DSB}$ = 500 K to 700 K in the Laboratory at frequencies from 500 GHz to 1.6 THz.
- Insensitive to bias conditions, saturation and direct detection effects.
- HEBs can absorb terahertz radiation up to the visible region (*freq* independent), well suited for spectroscopy.
- Lower noise than competing technologies (SIS mixers, SBD mixers).
- Quantum limited heterodyne measurement at the terahertz regime.
- Lower LO power (~10^4) than Schottky detectors.

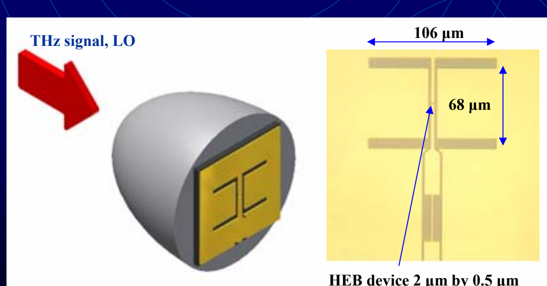


Quasi-Optical Design

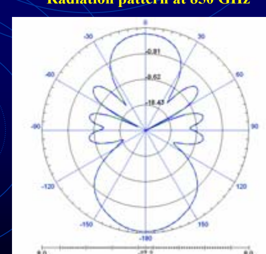
- A combination of a dielectric lens and a monolithic twin-slot antenna is used to couple the incoming radiation fields to the HEB device.
- Simulations of the reflection loss and the radiation pattern at different terahertz frequencies are performed.
- Off-axis parabolic mirrors are used as the beam focusing elements because of their low attenuation and distortion.

Reflection loss

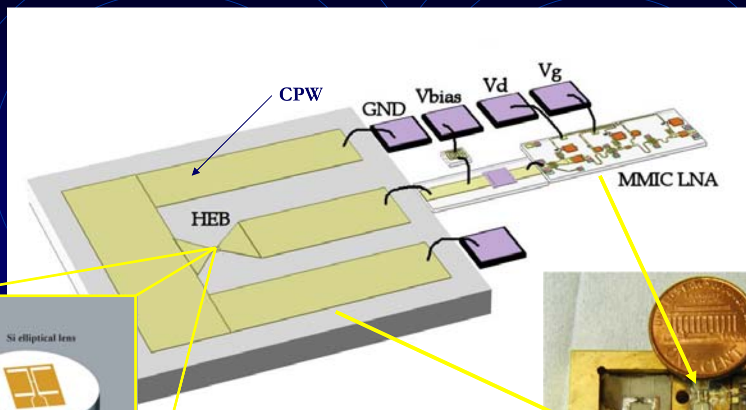


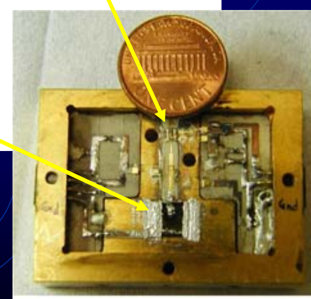


Radiation pattern at 850 GHz



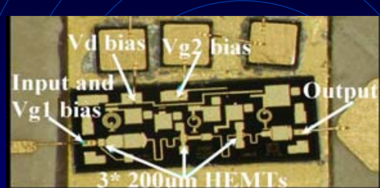
Mixer Block Integration





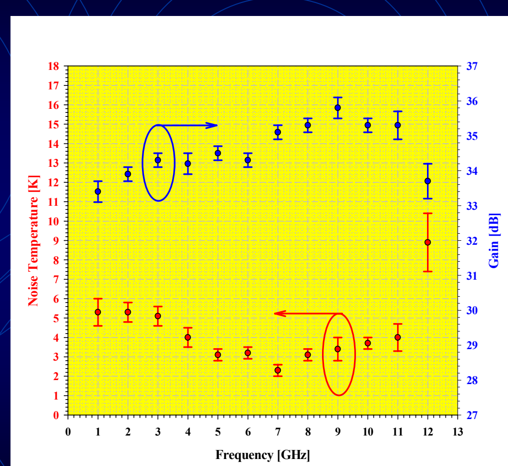
- MMIC low-noise amplifier and HEB mixer placed in the same plane reduces standing wave problem.
- All DC-bias and IF circuitry integrated in the same mixer block.

MMIC Low-Noise Amplifier



Developed by Dr. Sander Weinreb's group at JPL/Caltech

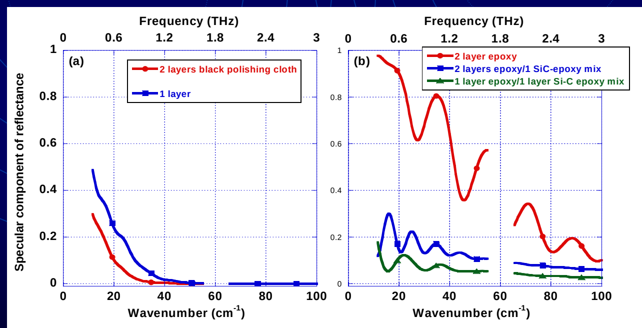
- Very broadband 3-stage InP HEMT MMIC LNA.
- Noise temperature nearly independent of bias settings.
- Remarkable noise performance: measured noise temperature below 5.5 K from 1 GHz to 11 GHz, with a minimum of 2.3K±0.3 K at 7 GHz.
- Low Power consumption.



J. Randa, E. Gerecht, D. Gu and R. Billinger, *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 3, pp. 1180-1189, March 2006.

Blackbody Standards

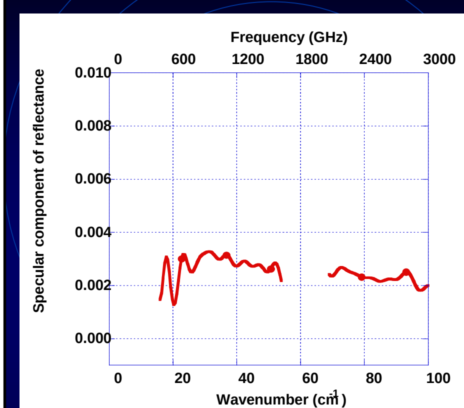
- Critical part of the system is the blackbody standards used to calibrate it. These are the fundamental standards to which the measurements will be "traceable."
- For the black body radiator, need to know the temperature and the emissivity in order to calculate the radiated power.
- Must know reflectance of coating, and whether it is specular or diffuse.
- Measurements of the specular component of reflectance for several materials of interest performed by Leonard Hansen and Simon Kaplan (NIST, Gaithersburg) are shown.

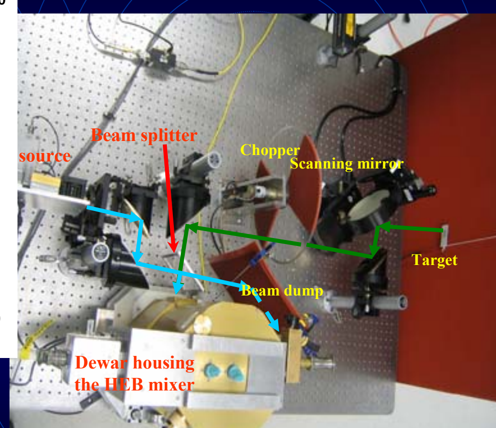


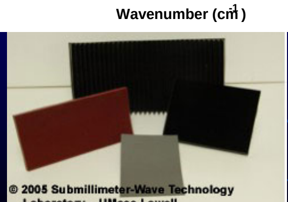
Specular reflectance component for different thicknesses of black cloth (left) and Si/C epoxy mixtures (right).

Reflection of the Ribbed Rubber Sheet Material

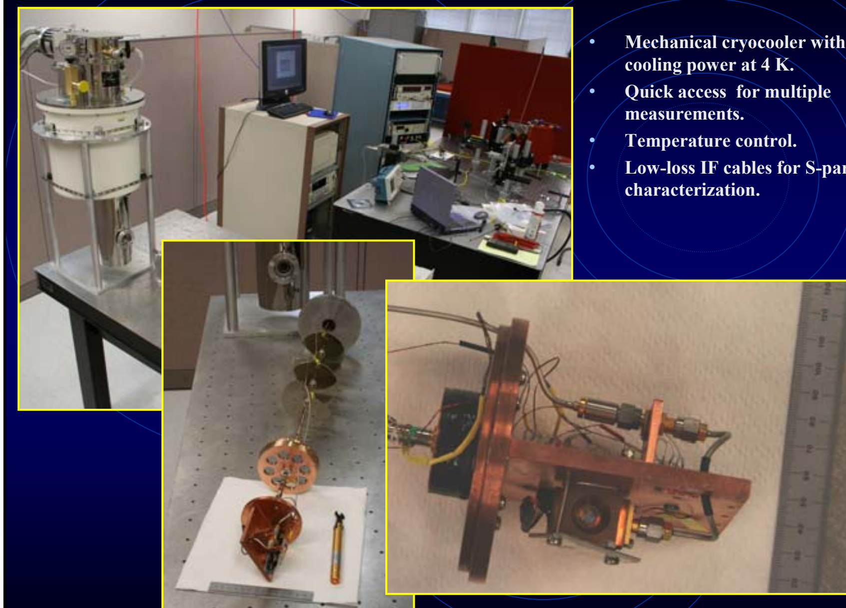
Simon Kaplan (NIST, Gaithersburg)







Cryogenic Setup



- Mechanical cryocooler with 1.5 W cooling power at 4 K.
- Quick access for multiple measurements.
- Temperature control.
- Low-loss IF cables for S-parameter characterization.

Summary

- Design for a terahertz radiometer for traceable noise-temperature measurements is presented.
- Demonstration of an HEB and MMIC LNA integration for the front-end of the radiometer.
- Measurements of blackbody materials for terahertz frequencies are presented.
- Future development includes the completion of the integration of the radiometer and a careful analysis of the system.